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Experimental Study into Droplet Formation in Steam Flows

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Abstract. Progress in the development of the steam turbines bring about a renewal of interest in wetness associated problems. Consequently, the present study investigates the droplet formation in low pressure steam flows. An experiment is conducted to measure the pressure ratio and size of the droplets developing in the divergent section of the convergent-divergent nozzle. The results obtained from the present study are compared with the existing data in the literature. It is found that the high rate of expansion results in large droplet size, which increases slightly as the stagnation pressure increases. In addition, the results obtained from the present analysis are in good agreement with the results of the previous study.

Key words: droplet formation measurement optical method.

1. Introduction

Use of steam in power generation is highly demanding in power plants. Many problems are encountered in designing the steam turbines and during their operation. Although well established theoretical models of flow in dry stages of steam turbine is available, comparatively little effort has been spent on developing treatments for the two phase stages [1, 2]. The expansion of wet steam could be associated with loss of efficiency, but this problem might be confined to the last stages of low pressure turbines. It should be noted that as in the case low pressures, the starting point of the wetness problems has been the study of nucleation in high pressure steam. On the other hand, the advent of water-cooled nuclear reactor, steam with little or no super heat is supplied to the high pressure turbine and therefore wetness problem has spread to all sections of the power plant [3]. In general, the most serious problem caused by the wetness the departure of the system from thermodynamic equilibrium. This is due to the release of latent heat which affects the attainment of equilibrium in the neighboring compressible vapor.

Considerable experimental and theoretical investigations have been carried out in the past to improve the efficiency of the turbine parts. Turbine entry losses was

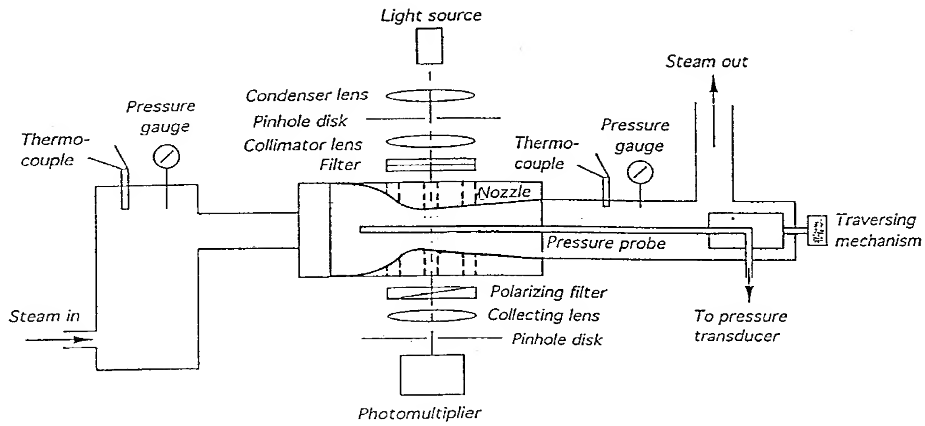

Figure 1. Experimental set up.

measured and predicted by Samoilovich et al. [4]. They showed that the losses, due to expansion through blade cascade, reduce the efficiency and degree of reaction. The optical fiber droplet sizer was used by Tatsumo and Nagao [5] to measure the water droplet size in steam turbine. They reported that average diameters between 0.2 and 1 μm depending upon wetness (6–14%) and locations in the radial direction of blade occurred. Experimental work in measuring the droplet size due to spontaneous nucleation was reported by Gyarmathy and Lesh [6] and Walters [7]. They have shown that the droplet radius increases with increasing droplet temperature upto the corresponding saturation temperature. The comprehensive work on the condensation and evaporation of liquid droplets in a pure vapor at arbitrary Knudsen number was conducted by Young [8]. The physical model used was based on modified Langmuir analysis. He developed the sets of equations governing the formation and evaporation of small liquid droplets in a pure vapor. However, more emphasis was given on the derivation of the energy equation as well as phenomenological coefficients relevant to mass transfer equation. He also demonstrated that the results of the analysis were in close agreement with the results obtained from other relevant analytical and numerical studies. The work provided very useful information across the Knudsen layer in the continuum limit. However, in the study, the explicit formulation of the rate of droplet growth was not giving for both free molecular and continuum flow regimes.

In the present study, the experiment is conducted to measure the size of the droplets when dry and wet steam flow through a nozzle. To achieve this, a convergent-divergent nozzle is designed and realized. The pressure distribution along the nozzle is obtained while the resulting droplet sizes are measured using an optical method for dry and wet steam conditions. The experiment is extended to include four stagnation pressures and two stagnation temperatures.

$\alpha = 0.8°$ $R_1 = 28$ mm $R_2 = 115$ mm

	x	y
A	0	0
B	12.4	-2.9
D	65	-15
F	153	-13.3
O_1	0	28
O_2	68	-100
T	63	-15

All the dimensions in the table are in mm.

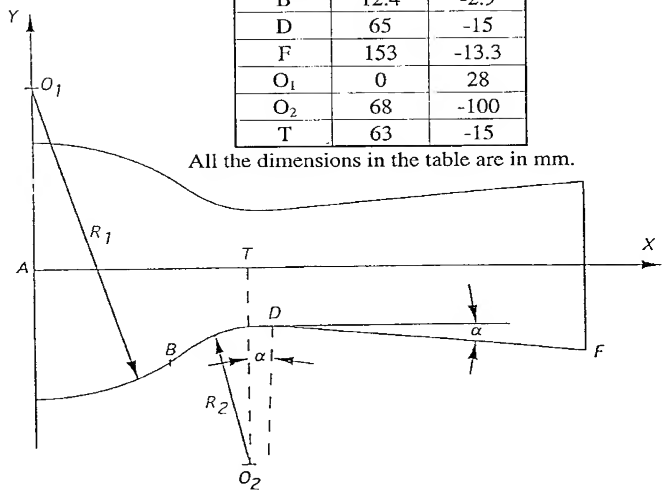

Figure 2. Nozzle dimensions.

2. Experimental

Experimental set up is shown in Figure 1. A convergent-divergent cylindrical nozzle was designed and realized. The layout of the nozzle is shown in Figure 2. The nozzle was manufactured from steel bar with half angles of divergence of 0.8°. Steam flowed from super heater through inlet receiver to test nozzle, where its temperature and pressure were measured. Static pressure along the nozzle was sensed by a 1.83 mm bore stodola search tube (probe). It was guided axially by several supports of which two are located one on each side of the nozzle. Small vent on pressure transducer mount was used to purge the air in the system prior to an experiment. The inlet total temperature of the steam was measured with copper-constantan thermocouple probe inserted through a gland housing into the inlet receiver and fitted with a radiation shield. All the measuring device outputs were fed into the computer and recorded simultaneously.

The experiment was carried out at four pressure levels and two values of inlet temperature. The highest values of the selected range gave an entirely dry static pressure distribution along the nozzle length, and the second setting was low enough for the typical pressure rise due to rapid condensation to occur within a distance of approximately 50 mm down stream of the throat.

An optical method was employed to measure the droplet size. The light from a mercury lamp source was condensed by a lens on to the first pinhole, which was placed at the focus of the collimator lens so that a parallel beam traversed

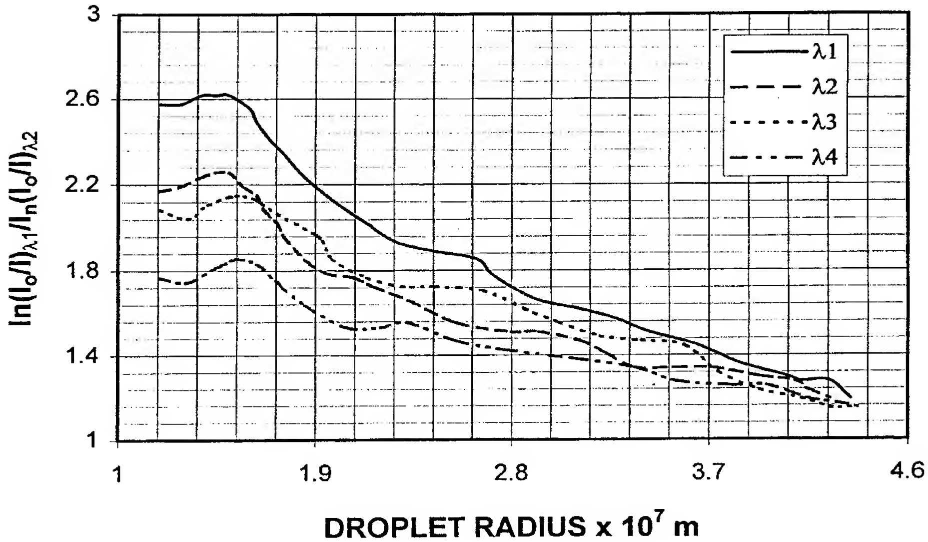

Figure 3. Calibration curves for the droplet size measurement.

the suspension in the flow channel. The attenuated beam emerging from the steam channel was collected by a lens and a second pinhole was placed before its intensity was measured by means of a photomultiplier. Two filters were set for selecting a single wavelength from the incoming rays and a polarizing filter was used to protect the photomultiplier from overloading. It was shown that scattered light collected would be negligible, if the angle subtended by the diameter of each pinhole at its lens was less than $0.384/\alpha$ radians [9]. With lenses having a 100 mm focal length and the largest particle diameter of 1.8 μm, the corresponding pinhole diameter was about 3 mm. The calibration curve for the droplet size is shown in Figure 3.

3. Measurement and Determination of Droplet Radius

The droplet size measurement relies on the light scattering technique, The energy scattered and absorbed by a droplet is determined by a scattering coefficient or efficiency factor q, which is defined as:

$$q = \frac{\text{Total flux scattered and absorbed by a particle}}{\text{Flux geometrically incident on the particle}} .$$

The extinction coefficient k can be defined according to Lambert's law as:

$$k = -\frac{1}{l} \ln \frac{I_o}{I} ,$$

where I_o is the incident light intensity, I is the transmitted light intensity at the end of the distance l. Once the scattering coefficient is known, the extinction coefficient k can be simply calculated from:

$$k = \pi r^2 N q,$$

where r denotes the radius and N the volume concentration of the suspended particles. The product kl is known as the turbidity and the ratio I/I_o is called transmittance of the medium. The scattering coefficient q is a function of the light wavelength λ, the refractive index n of the particle relative to the suspending medium, and the size parameter α. For the case of water droplets having refractive index of 1.33, the extensive computations were carried out and the results were tabulated [10].

The average radius of droplets contained in an approximately mono-dispersed suspension can be determined with the use of Figure 3. Each curve illustrates the variation of droplet radius with the attenuated intensity of a monochromatic light beam at various wavelengths. The method consists in determining experimental values of transmittance (I/I_o) for at least two wavelengths, calculating the ratio of their logarithms and by reference to Figure 3 reading the corresponding droplet radius. On the other hand, combination of equations of transmittance and extinction coefficient corresponding to two selected wavelengths gives:

$$\ln\left(\frac{I}{I_o}\right)_{\lambda_1} = q_1 \pi r^2 N l$$

and

$$\ln\left(\frac{I}{I_o}\right)_{\lambda_2} = q_2 \pi r^2 N l,$$

or dividing them yields:

$$\frac{q_1}{q_2} = \frac{\ln(I_o/I)_{\lambda_1}}{\ln(I_o/I)_{\lambda_2}}\ .$$

Since wavelength λ_1 and λ_2 as well as refractive index are known, the scattering coefficients q_1 and q_2 can be read off published tables over a range of droplet radii. The ratio q_1/q_2 is then plotted directly against corresponding values of droplet radius r.

4. Results and Discussion

The pressure variation across the converging-diverging nozzle was obtained successfully using a stodola probe for dry and wet steam conditions. The resulting droplet radius was measured using the optical system. Consequently, the results obtained from the present work will be discussed as follows.

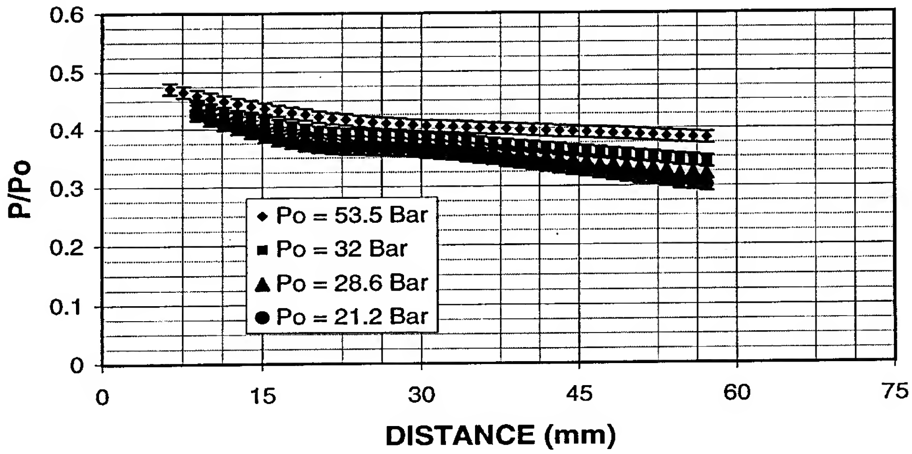

Figure 4. Variation of P/P_o with distance from the nozzle throat (the measurements were conducted at the centerline of the nozzle, $y = 0$.

Figure 4 shows pressure ratio (P/P_o) with the distance from the nozzle throat, where P_o is the stagnation pressure. The general trend is that P/P_o decreases as the distance along the nozzle increases. This may be due to the occurrence of high expansion rate at high divergency. The rate of drop in P/P_o just immediately after the nozzle throat is almost constant and this extends to the distance of about 25 mm from the nozzle throat. However, rapid drop in P/P_o occurs at around this point, indicating the sudden increase in nucleation rate, which in turn increases the rate of supercooling of the steam in this region.

Figure 5 shows the variation of droplet radius, both predicted and experimentally obtained, with the distance from the throat of the nozzles. The droplet radius increases as the expansion rate increases. However, at small rates of expansion, the steam supercools and reverts to equilibrium at a slower rate and the condensation zone is stretched over a longer distance. The main consequence of the small rate of change of pressure is to allow the first centers of condensation generated to grow large enough so that the latent heat released reduces the rate of increase of supercooling and the subsequent value of the nucleation current. Moreover, sudden increase in droplet radius occurs after 25 mm downstream from the nozzle throat, in this case, pressure drops further (Figure 4) resulting in sudden expansion, which in turn increases the rate of supercooling. When comparing the present results with the Tubman's [11] findings it is evident that the results obtained from the Tubman's work give relatively larger droplet radius than the present results. This may be due to the either measurement errors and/or experimental conditions.

The location of Wilson point is carried out when dry and condensing static pressure curves first separate, in this case; the nozzle isentropic efficiency is considered as 93%. The values of parameters at the Wilson points are given in Table I.

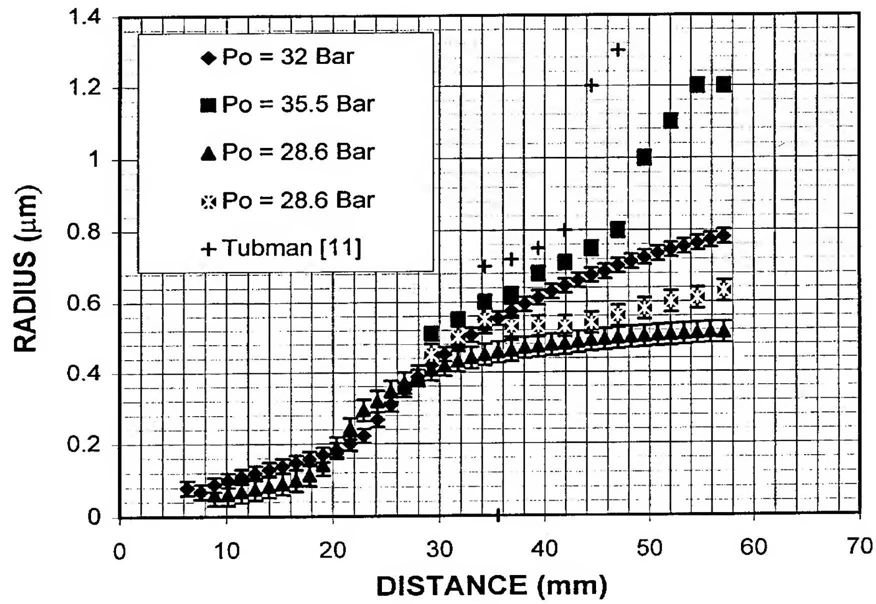

Figure 5. Variation of droplet radius corresponding to present results and previous experiments with distance from throat of the nozzle (the measurements were conducted at the centerline of the nozzle, $y = 0$).

Table I. Stagnation pressures and temperatures.

Source of variation	1	2	3	4
P (bar)	35.5	32	28.6	21.2
T_0 (K)	542	535	530	521

The value of the rate of expansion taken as 0.25 mm prior to the maximum supersaturation is almost constant. The supersaturation ratio (S^*) and degree of super cooling (ΔT^*) are plotted with Wilson point pressure (P^*) in Figures 6 and 7. The effect of (P^*) is considerable at low expansion rate. The scatter points for the low rate of expansion may be explained in terms of the sensitivity of the droplet size with expansion rate, i.e. the droplet radius is inversely proportional to the rate of expansion.

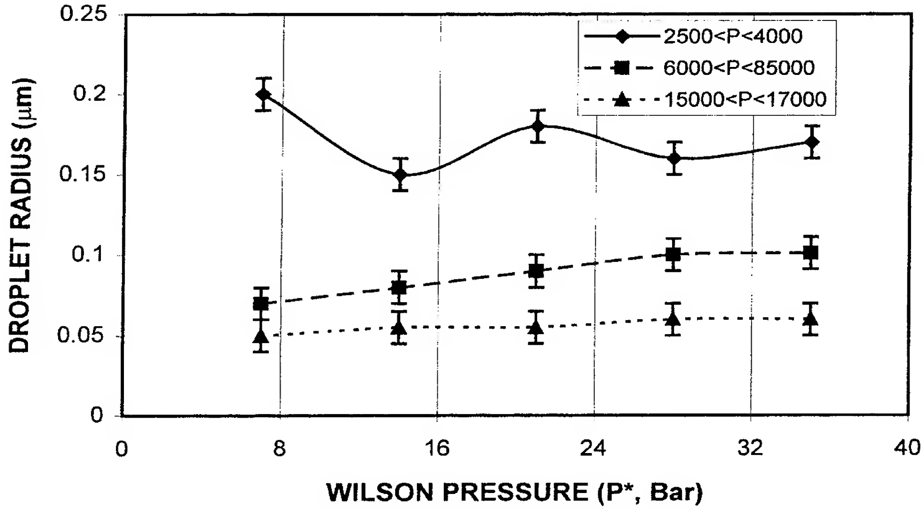

Figure 6. Variation of droplet radius with Wilson pressure as expansion rate is variable (P is the expansion rate).

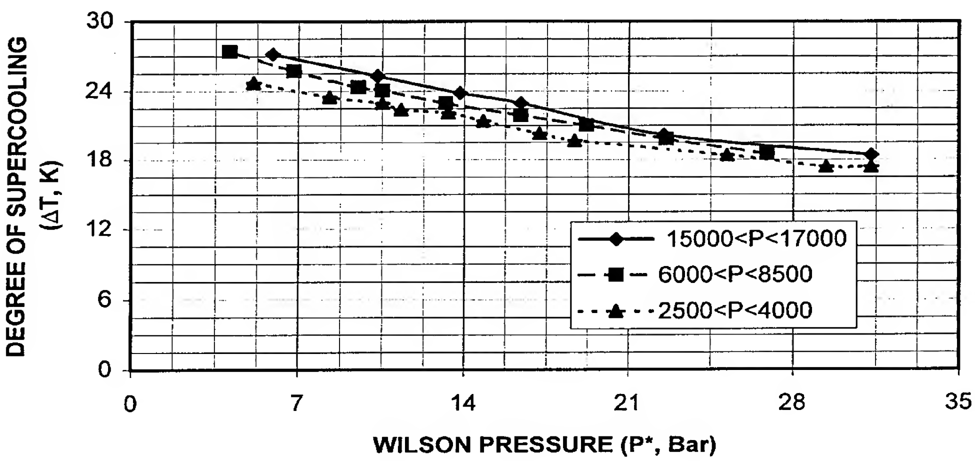

Figure 7. Variation of degree of supercooling with Wilson point pressure as expansion rate is variable (P is the expansion rate).

5. Conclusions

The pressure variation along a convergent-divergent nozzle was obtained employing a stodola probe while the droplet size was measured using an optical method. The droplet radius obtained from the previous study is found to be smaller than that corresponds to the previous measurement results. This may be due to the error related to the measurement, i.e. in the previous study an ordinary light source was

used, which in turn results in wide spectrum of spectral emission. In this case; the overall beam power absorbed by the droplets increases, therefore, I/I_o ratio increases. Nevertheless, the experimental results are found to be in good agreement with the previous measurement results. On the other hand, the small rate of pressure change demonstrates that the condensation center grows giving rise to latent heat being released, which in turn reduces the rate of increase of supercooling. Higher the rate of expansion results in larger the droplet size. In addition, the droplet size increases slightly as the stagnation pressure increases.

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